④

AD-A202 545

Office of the Chief of Naval Research
Contract N00014-85-0187
Technical Report No. UWA/DME/TR-88/61

FURTHER STUDIES OF THE HRR FIELD OF A MOVING CRACK, AN EXPERIMENTAL ANALYSIS

Mahyar S. Dadkhah and Albert S. Kobayashi

December 1988

Department of Mechanical Engineering
College of Engineering
University of Washington

DTIC
ELECTE
22 JAN 1989
E

89   1 19   043

FURTHER STUDIES OF THE HRR FIELD OF A MOVING CRACK, AN EXPERIMENTAL ANLYSIS

Mahyar S. Dadkhah* and Albert S. Kobayashi**

*Rockwell International Science Center, Thousand Oaks, California   91360

**University of Washington, FU-10, Seattle, Washington   98195

ABSTRACT

An improved moire interferometry was used to record simultaneously both the vertical and horizontal displacements associated with stable crack growth in an uniaxially loaded 5052-H32 aluminum, single edge notched specimens. For stable crack growth up to 2 mm, the vertical displacement field showed the dominance of the HRR field. HRR field was detected in the horizontal displacement only at the initial stage of loading. The far and near field J-integrals were path independent during this incremental crack extension. These results and previous results involving 2024-0 and 2024-T3 aluminum specimens indicate that J-characterization of a crack, is not valid for such ductile materials in this specimen configuration. $\left(J^* \right)$

INTRODUCTION

One of the most popular fracture criterion in nonlinear fracture mechanics is RIC 's [1968] J-integral concept for which large developmental efforts, experimental and theoretical, have been expended for the past fifteen years. For a nonlinear elastic solid, the J-integral is path independent and thus the experimentally more accessible far-field J-integral value can be used to characterize the crack tip field. Furthermore, SHIH, DELORENZI and ANDREWS [1979] showed, through finite element analysis, that this path independency holds for small crack extension of about 5 mm in real engineering materials.

Physically, the J-integral value for a nonlinear elastic solid is the energy release rate which reduces to the familiar strain energy release rate for a linearly elastic solid. For a power hardening elastic-plastic material, HUTCHINSON [1968] and RICE and ROSENGREN [1968] showed that the extent of J-dominated crack tip region, which is commonly referred to as the HRR field, is characterized by this single parameter. MCMEEKING and PARKS [1979] and SHIH [1985] used finite element analysis to study the extent of the HRR fields in bend and tension fracture specimens. Both studies concluded that the HRR field is severely reduced in the tension specimens. The HRR field has been studied experimentally using the projection moire technique by CHIANG and HAREESH [1986]. This study showed that except for the very vicinity of the crack tip, the HRR field was a reasonable representation of the crack tip field. More recently, DADKHAH and KOBAYASHI [1989] showed through moire interferometry that the dominant displacement component, which is perpendicular to the crack, may conform with the corresponding HRR component but the displacement component parallel to the crack remained elastic and thus violated the premise of the HRR field.

The objective of this paper is to present further experimental evidence on the above and to discuss the significance of these and previously presented results.

EXPERIMENTAL PROCEDURE

The vertical and horizontal displacements in an uniaxially loaded 5052-H32 aluminum, single-edged notched plate were determined by an improved moire interferometry. Figure 1 shows the specimen configuration which was loaded in a special testing machine (HAWONG, KOBAYASHI, DADKHAH, KANG, RAMULU, [1987]). Figure 2a shows four results of uniaxial stress-strain tension tests in the vertical and horizontal directions for the 0.8 mm thick 5052-H32 aluminum alloy plate which were used in this study. The stress-strain relations for the vertical and horizontal directions for this plate were found to be within 5% of the experimental data shown in Figure 2a. Figure 2b shows the two parameters for the corresponding power hardening relation which was fitted to average of the four tests in Figure 2a.

The improved moire interferometry is based on the four beam arrangement [POST, 1987] with an additional beam splitter and a prism which records simultaneously the vertical and horizontal displacements in a single frame (DADKHAH, WANG and KOBAYASHI, [1988]). This method removes the approximation, which was necessary in previous studies (KANG, KOBAYASHI and POST, [1987]; KANG and KOBAYASHI, [1988]), in the J-estimation. It is conducive for high speed photographic recording of the transient moire fringes associated with a rapidly propagating crack. For this study, the moire fringes during stable crack growth were recorded by a motorized Nikon camera.

An AST Turboscan Digitizer and a Macintosh II computer were used to digitize the photographically recorded moire fringes. A software was developed to compute the two-dimensional strain components from the recorded displacement field. These strain components were used to compute the J-integral value along given rectangular contours, which encompass the crack tip, as shown in Figure 1 (DADKHAH, KOBAYASHI, WANG and GRAESSER, [1988]).

J-INTEGRAL EVALUATION

The evaluation of the J-Integral requires the strain components, the stress components and the strain energy density at each data along the contours (RICE, [1968]). KING and HERRMANN [1981] used measured strains along the two traction-free edges of a centrally cracked tensile specimen to determine the J-integral. Measured strains have also been used by (MACKENZIE, MCKELVIE and WALKER, [1986]; MULLER and GROSS, [1980]; KAWAHARA and BRANDON, [1982]; READ, [1983]) to determine J experimentally. Each procedure was somewhat limited in its applicability due to difficulties encountered in measuring the rotation terms, $\partial u/\partial y$ and $\partial v/\partial x$, simultaneously.

A major advantage which is gained by using the four-beam arrangement (POST, [1987]) is that both $\partial u/\partial y$ and $\partial v/\partial x$ can be quantified directly from the in-plane u- and v-displacement fields which are represented by the two moire fringe patterns. The J-measurement, which is derived for rectangular contours surrounding the crack tip, is

3

first divided into line integrals along the vertical and horizontal segments as shown in Figure 1. The integral value of J along the vertical segments is:

$$J_V = \int_{V_1} \left[W - \left(\sigma_{xx} \frac{\partial u}{\partial x} + \tau_{xy} \frac{\partial v}{\partial x} \right) \right] dy - \int_{V_2} \left[W - \left(\sigma_{xx} \frac{\partial u}{\partial x} + \tau_{xy} \frac{\partial v}{\partial x} \right) \right] dy \quad (1)$$

and along the horizontal segments, the value of J is:

$$J_H = \int_{H_1} \left[W - \left(\sigma_{xx} \frac{\partial u}{\partial x} + \tau_{xy} \frac{\partial v}{\partial x} \right) \right] dx + \int_{H_2} \left[W - \left(\sigma_{xx} \frac{\partial u}{\partial x} + \tau_{xy} \frac{\partial v}{\partial x} \right) \right] dx \quad (2)$$

Using the J_2-deformation theory for multiaxial states, the strains in the vicinity of a crack tip in a power hardening material is represented by

$$\varepsilon_{ij}/\varepsilon_0 = 3/2 \ \alpha(\sigma_e/\sigma_0)^{n-1} \ S_{ij} \quad (3)$$

and

$$\sigma_e = (3/2 \ S_{ij}S_{ij})^{1/2} \quad (4)$$

where S_{ij} is the deviatoric stress, and $\varepsilon = \frac{\sigma_0}{E}$ is uniaxial strain with E as modulus of elasticity. σ_0 is the yield stress and α and n are two the disposal parameters to fit the power law hardening stress-strain relation with the uniaxial tensile data.

For the state of generalized plane stress, the stress-strain relations for this power hardening material can be expressed in the following matrix forms;

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} = \begin{pmatrix} (1+F) & (v+F/2) & 0 \\ (v+F/2) & (1+F) & 0 \\ 0 & 0 & [2(1-v)/2+F/4] \end{pmatrix} \begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ 2\varepsilon_{xy} \end{pmatrix} \quad (5)$$

4

where E and ν are the modulus of elasticity and Poison's ratio, respectively, and

$$F = \alpha \, \sigma_e^{n-1}$$

$$\gamma = (1+\nu+1.5F)(1-\nu+0.5F)$$

$$\sigma_e^2 = \sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau_{xy}^2$$

Strain energy density W is defined as:

$$W = \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij}$$

$$W = \frac{1}{E}\left\{ \frac{1+\nu}{3}\sigma_e^2 + \frac{1+2\nu}{6}\sigma_{kk}^2 + \frac{\alpha n}{n+1}\sigma_e^2 \left(\frac{\sigma_e}{\sigma_0}\right)^{n-1} \right\} \tag{6}$$

where σ_0 is the yield stress.

The resultant J-integral value for this problem is given by

$$J = J_V + J_H \tag{7}$$

Accuracy of this procedure was assessed by evaluating equs. (1) and (2) along a 4.2 cm contour, which did not enclose the crack tip, using the moire fringe data. The resultant J= 49.0 (Pa-m), which theoretically should vanish, was 0.4 % of the minimum recorded J-value in this study.

5

Path independency of the J-integral during stable crack growth was evaluated using a series of rectangular paths encompassing the extending crack tip: as shown in Figure 1.

HRR FIELD

For a power hardening material, the r^{-1} singularity in W implies a $r^{-1/(n+1)}$ singularity in the stresses, a $r^{-n/(n+1)}$ singularity in the strains, and a $r^{1/(n+1)}$ variation in the displacements. The near-crack tip singularity fields can be written as

$$\sigma_{ij} = \sigma_0 \left(\frac{J}{\alpha\sigma_0\varepsilon_0 I_n r} \right)^{1/n+1} \tilde{\sigma}_{ij}(\theta, n) \tag{9}$$

$$\varepsilon_{ij} = \alpha\,\varepsilon_0 \left(\frac{J}{\alpha\sigma_0\varepsilon_0 I_n r} \right)^{n/n+1} \tilde{\varepsilon}_{ij}(\theta, n) \tag{10}$$

$$u_i - u_i = \alpha\,\varepsilon_0 r \left(\frac{J}{\alpha\sigma_0\varepsilon_0 I_n r} \right)^{n/n+1} \tilde{u}_i(\theta, n) \tag{11}$$

The dimensionless θ- variations of $\tilde{\sigma}_{ij}(\theta, n)$, $\tilde{\varepsilon}_{ij}(\theta, n)$ and $\tilde{u}_i(\theta, n)$ and the normalizing constant I_n depend on the fracture mode, on n and on the state of plane strain or plane stress. These variations must be normalized in some manner and thus the maximum value of $\tilde{\sigma}_e = 3/2\,(S_{ij}\cdot S_{ij})^{1/2}$ was set to unity in this study. The contribution in $\tilde{u}_i$ allows for a possible translation of the crack tip.

RESULTS

One 5052-H32 aluminum cruciform specimen was loaded uniaxially to generate a stable crack growth length of $\Delta a = 2$ mm at which point the experiment was terminated since

6

the moire fringes became too dense and indistinguisable. Figure 3 shows the load versus load-line displacement relation for this uniaxially loaded 5052-H32 aluminum cruciform specimen.

Figures 4a and 4b show typical moire fringes, i.e., the vertical displacement, v, and the horizontal displacement, u. Also shown are typical integration contours used for the J-integral evaluation. The J values obtained along these contours are shown in Table 1. Path independence, i.e., within a eight percent scatter in the J-values, is noted. The J-integral values which were computed (SHIH, GERMAN and KUMAR [1981]) by using the results of Figure 1, are also shown for comparison in Table 1. The specimen of the single edge notched specimen under uniaxial tension used in this computation was set to b = 85.7 mm .

Figure 5 and 6 show typical log-log plots of the v- and u-displacement fields obtained from the moire fringes at a crack extension of Δa = 1.95 mm. The load for these recording can be found from Fig. 1. Also shown are the log-log plots of the displacements versus radial distance, r, of the linear elastic fracture mechanics (LEFM) and HRR fields at a crack tip polar angle of $\theta = 45°$. The LEFM field was obtained by computing the equivalent stress intensity factor from the average J-value obtained from the contour integration. The HRR field was obtained by substituting this average J-value into equ. (11). The HRR field requires that the slope of the log-log plots be a constant of $1/(n + 1)$, which is 0.059 for the 5052-H32 aluminum used in this study. These plots indicate that the v-field conformed with the HRR field requirement at a radial distance approximately 7 mm away from the crack tip. The nonlinear zone as gleaned from Fig. 5a, (HUTCHINSON, [1983]) thus extends 7 mm from the crack tip along θ = 45°. The u-field, on the other hand, conformed with the LEFM crack tip field beyond the 7mm radial distance and had a much smaller strain singularity inside of this 7 mm boundary. This nonlinear region in 5052-H32 aluminum alloy is much larger than 2024-0 and 2024-T3 aluminum alloys (DADKHAH and KOBAYASHI [1989]. A total of fourteen log-log plots of the u- and v-fields obtained in this study were evaluated to arrive at the conclusion that only the v-field exhibited the HRR field through the loading and stable crack growth process.

Figure 7 and 8 shows plots of the measured v- and u-displacements at a point of r = 1.2 and 5 mm, respectively (1.5 and 6.3 times the plate thickness) and at θ = 45°, where HRR field was shown to extend the furthest (CHIANG and HAREESH, [1986]), with increasing applied load. Also shown are the corresponding u- and v-displacement fields for the LEFM and HRR fields at the same location. These results show that the region of r = 1.2 mm is entrenched in the nonlinear zone while the v-displacement of r ≈ 5 mm follows the HRR field throughout the entire loading. The u-displacement field, on the other hand, fell away from the HRR after the initial loading.

Figure 9 shows the traditional J-resistance curve of this 5052-H32 specimen. Also shown are the approximate J-integral values which were reported by KANG and KOBAYASHI [1987], for the same material but for a much smaller conventional single edge notched specimen. These J-resistance curves differ with others in that crack extension occurs at a very low applied load without the significant blunting as reported by PARIS, TADA, ZAHOOR and ERNST [1979].

DISCUSSIONS

The results described in this paper are in complete agreement with those for the less ductile 2024-0 and 2024-T3 aluminum cruciform specimens by DADKHAH and KOBAYASHI [1989]. Figures 10 and 11 show typical variations of the measured v-and u-displacement fields respectively, in identical 2024-0 and 2024-T3 aluminum specimen together with the corresponding displacements for HRR and LEFM fields at a radial distance of r = 1.2 mm and polar angle of θ = 45° from the crack tip. Unlike the 5052-H32 aluminum specimen the v-displacement in the more strain hardening 2024-0 and 2024-T3 aluminum alloy followed the HRR field throughout the stable crack growth of Δa = 2 mm. The u-displacement field, on the other hand, exhibited the same trend of falling away from the HRR field after the quarter of the loading phase. These results are in agreement with the replotted experimental results (HU and LIU [1976]) of KE and LIU [1973] who used geometric moire method to detemine the dominant strain component in 2024-0 aluminum double-edge-notched specimens.

It should be noted that this present discussion is limited to the analysis of HRR region of a moving crack in plane stress conditions. This and the above referenced previous results of DADKHAH and KOBAYASHI [1989] both showed that only the v-field exhibited the expected progression from the LEFM to the HRR crack tip fields with increasing load. Unlike 2024-0 and 2024-T3, the v-displacement in the more ductile 5052-H32 (n = 16) deviated from the corresponding HRR component at a higher loading where the HRR singularity field prevailed in the former two aluminum alloys. The u-displacement fields in both the 2024-0 and 5052-H32 speciinens deviated from the corresponding HRR field at the very earlier stages of loading. Figure 2 shows that anisotropy in the rolled aluminum alloy sheet could hardly contribute to this deviation for the 5052-H32 specimen. Similar disclaimers are gleaned from the uniaxial stress-strain data of 2024-0 and 2024-T3, rolled aluminum sheets.

The above results are in disagreement with the requirements for the J-dominant region for plane strain condition by HUTCHINSON [1983] and SHIH [1985] where both the u- and v-displacement conformed with those of the HRR field. These results thus indicate that *the desired HRR field does not exist in ductile materials* and that J in this case is not a parameter which characterizes the crack tip singularity. J should thus be considered a contour integral, as defined by eqns. (1) and (2), and appears to be path independent for the small crack extension of approximately 2 mm considered in this study. The J-integral could thus be used as a far field parameter provided it is not used to characterize crack tip field,

Finally, one notes that the deformation theory of plasticity was used to compute the stresses fur the contour integration in eqn. (3) t.irough (6). Which are opened to experimental scrutiny. The path independency check and the vanishing J along a contour, which did not contain the crack tip, indirectly validate the use of deformation theory of plasticity in this study.

The large deviations, as shown in Table 1, between the J-values estimated by using SHIH, GERMAN and KUMAR [1981] formula requires further investigation. Since the cruciform specimen used in this study is substantially different in geometry with the

9

conventional single-edge notched specimen used by SHIH, GERMAN and KUMAR [1985], any conclusion regarding his formula is strictly speculative at this time.

CONCLUSIONS

1) HRR field existed in the v-field during the stable crack growth process in a region beyond the nonlinear zone at the crack tip.

2) LEFM field existed in the for u-field beyond the nonlinear zone.

3) J is path independent for a small crack extension of 2 mm in 5052-H32 aluminum alloy.

ACKNOWLEDGEMENT

REFERENCES

1968 HUTCHINSON, J.W., "Singular Behavior at the End of A Tensile Crack in A Hardening Material," J. of Mechanics and Physics of Solids, 16, 13-31.

1968 RICE, J.R., "A Path-independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks," ASME J. of Applied Mechanics, 35, 379-386.

1968 RICE, J.R. and ROSENGREN, G.F., "Plane-Strain Deformation Near a Crack Tip in a Power-Hardening Material," J. of Mechanics and Physics of Solids, 16, 1-12.

1973 KE, J.S. and LIU, H.W., "The Measurements of Fracture Toughness of Ductile Materials,"Engineering Fracture Mechanics, 5, (1), 187-202.

1976 HU, W.-L. and LIU, H.W., "Crack Tip Strain--A Comparison of Finite Element Method Calculations and Moire Measurements," Crack and Fracture, ASTM STP 601, 522-534.

1979 MCMEEKING, R.M. and PARKS, D.M., "On Criteria for J-Dominance of Crack-Tip Fields in Large Scale Yielding," in LANDES, J.D., BEGLEY, J.A. and CLARKE, G.A. (eds), Elastic-Plastic Fracture, ASTM STP 669, 175-194.

1979 PARIS, P.C., TADA,H., ZAHOOR, A. and ERNST, H., "The Theory of Instability of Tearing Mode of Elastic-Plastic Crack Growth," Elastic-Plastic Fracture, in LANDES, J.D., BEGLEY, J.A. and CLARKE, G.A. (eds.), ASTM STP 668, 5-36.

1979 SHIH, C.F., DELORENZI, R.G. and ANDREWS, W.R., "Studies on Crack Initiation and Stable Crack Growth," in LANDES, J.D., BEGLEY, J.A. and CLARKE, G.A. (eds), Elastic-Plastic Fracture, ASTM STP 668, 65-120

1980 MULLER, T. and GROSS, D., "Experimental Investigations of the Path Independence of the J-integral for Large Plastic Zones," Proc. 3rd European Colloquium on Fracture, London.

1981 KING, R.B. and HERRMANN, G., "Nondestructive Evaluation of the J and M Integrals," ASME J. of Applied Mechanics, 48, 83-87.

1981 SHIH, C.F., GERMAN, M.D. and KUMAR, V., "An Engineering Approach for Examining Crack Growth and Stability in Flawed Structures," Int. J. of Pressure Vessels and Piping, 9, 159-196.

1982 KAWAHARA, W.A. and BRANDON, S.L., "J-Integral Evaluation by Resistance Strain Guages," Proc. SESA/JSME Spring Meeting, May.

1983 HUTCHINSON, J.W., "Fundamentals of the Phenomenological Theory of Nonlinear Fracture Mechanics," ASME J. of Applied Mechanics, 50, 1042-1051.

1983 READ, D.T., "Experimental Method for Direct Evaluation of the J-Contour Integral," Fracture Mechanics: Fourteenth Symposium - Vol. II: Testing and Applications, ASTM STP 791, II 199- II 213.

1985 SHIH, C.F., "J-dominance Under Plane Strain Fully Plastic Conditions: The Edge Crack Panel Subjected to Combined Tension and Bending," Int. J. Fracture, 29, 73-84.

1986 CHIANG, F.P. and HAREESH, T.V., "An Experimental Study of Crack Tip Fields by the HRR Singularity," Proc. of 1986 SEM Spring Conference on Experimental Mechanics, 782-783.

1986 MACKENZIE, P.M., MCKELVIE, J., and WALKER, C.A., "Evaluation of the J-integral using A High-Sensitivity Moire Technique," Proc. of the 1986 SEM Spring Conference on Experimental Mechanics, New Orleans, 773-780.

1987 HAWONG, J.S., KOBAYASHI, A.S., DADKHAH, M.S., KANG, B.S.-J. and RAMULU, M., "Dynamic Crack Curving and Branching Under Biaxial Loading," Experimental Mechanics, 27, 146.

1987 KANG, B.S.-J. and KOBAYASHI, A.S., "J-Resistance Curves in Aluminum SEN Specimens Using Moire Interferometry," Experimental Mechanics, 28, 154-158.

1987 POST,D., "Moire Interferometry" in KOBAYASHI, A.S. (ed) Handbook of Experimental Mechanics, Prentice Hall, 314-387.

1988 DADKHAH, M.S., KOBAYASHI, A.S., WANG, F.X. and GRAESSER, D.L., "J.-Integral Measurements Using Moire Interferometry," Proc. of the Vi Int. Congress on Experimental Mechanics, 227-234.

1988 DADKHAH, M.S., WANG, F.X. and KOBAYASHI, A.S., "Simultaneous On-Line Measurement of Orthogonal Displacement Fields by Moire Interferometry," Experimental Techniques, 12, 28-30.

1989 DADKHAH, M.S. and KOBAYASHI, A.S., "HRR Field of a Moving Crack, An Experimental Analysis," to be published in Eng. Fracture Mechanics.

Table 1. J-Integral Values Under Stable Crack Growth
in 5052-H32 Aluminum Specimen, MD031188(1)

Load in Y direction (N)	J (kPa-m)			Δa (mm)
	Contour I	Contour 2	SHIH ET AL [1981] b = 85.7 mm	
2370	4.8	5.2	3.9	0.0
3810	8.0	7.3	10.0	0.2
4400	12.9	11.6	14.8	0.36
52.50	18.6	17.1	22.2	0.5
5760	23.8	25.3	29.6	0.75
6780	42.8	40.4	430.	1.35
7460	66.7	64.7	430.	1.95

ASK/cm:bfp

14
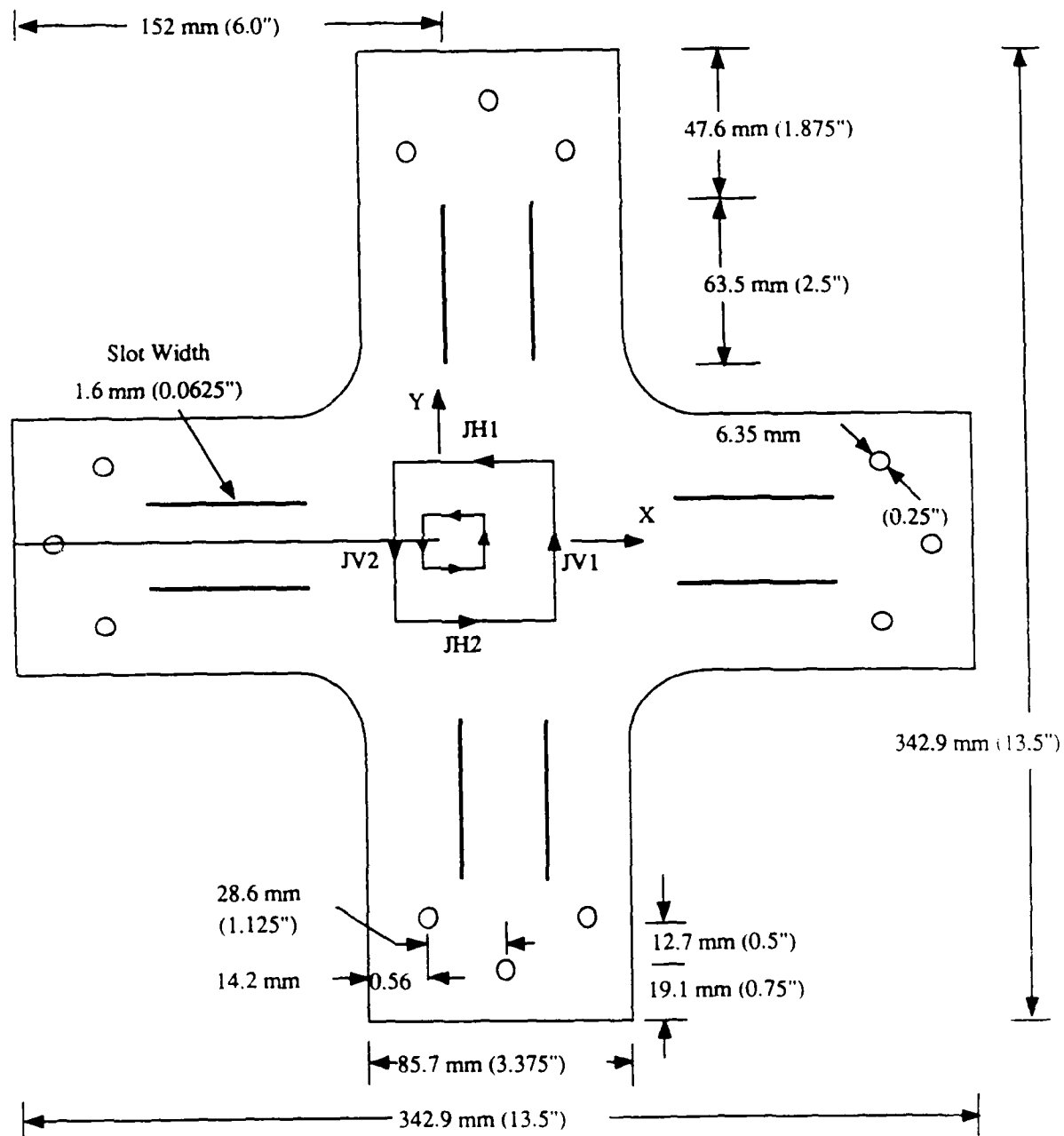
Figure 1. Specimen Configuration and J-integral Paths
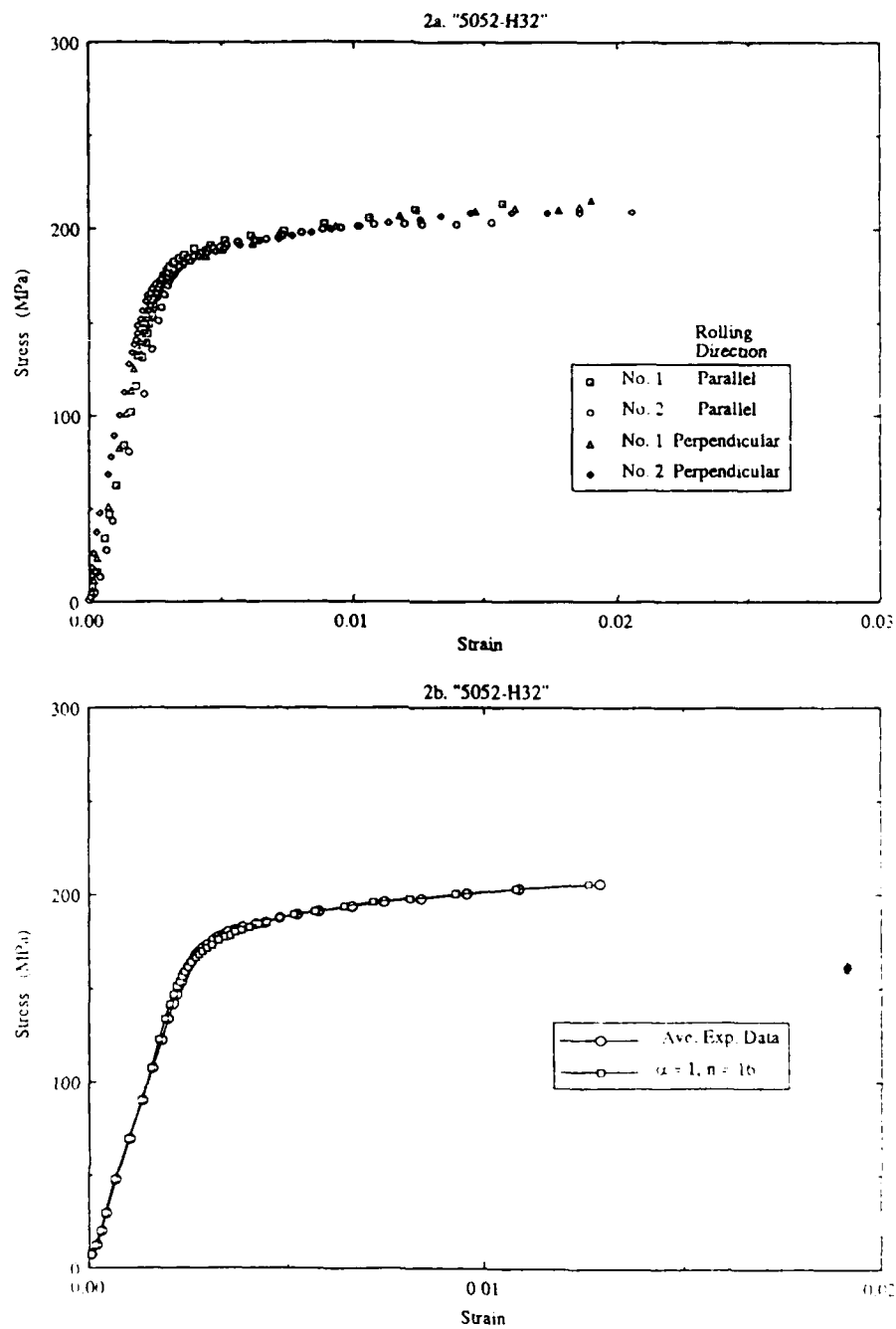
Figure 2.   Uniaxial Stress-Strain Curve for 5052-H32.

Load-Load Line Disp. 5052-H32
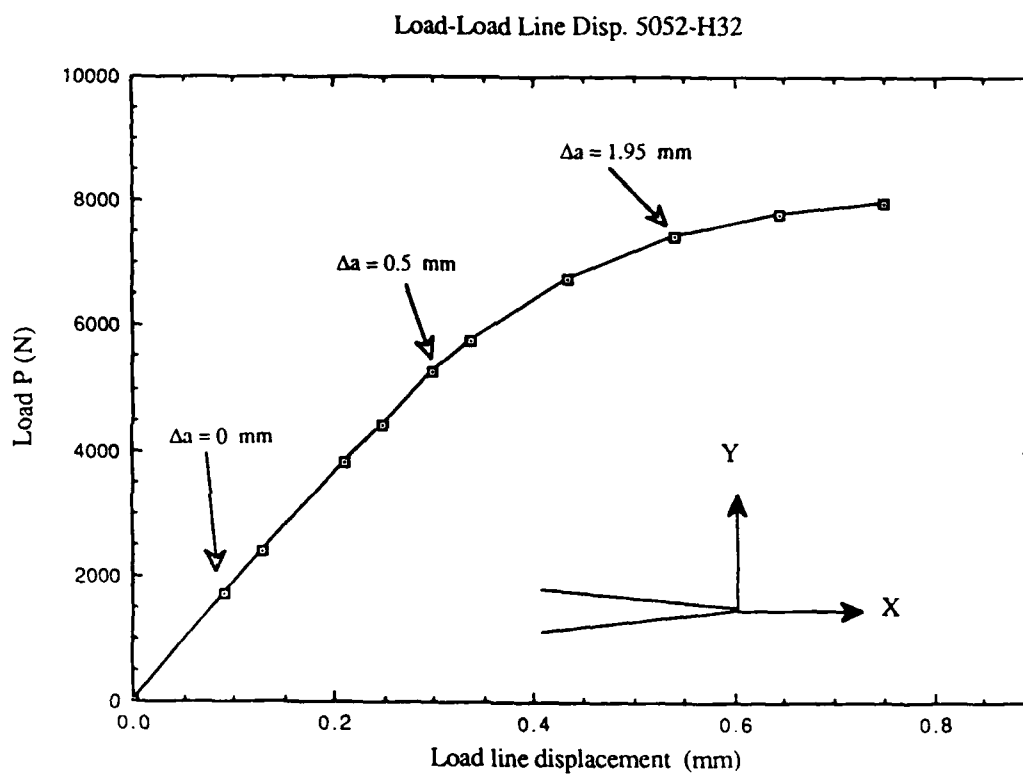
Figure 3.   Load versus Load-line Displacement in 5052-H32 Aluminum Specimen, MD031188(1).
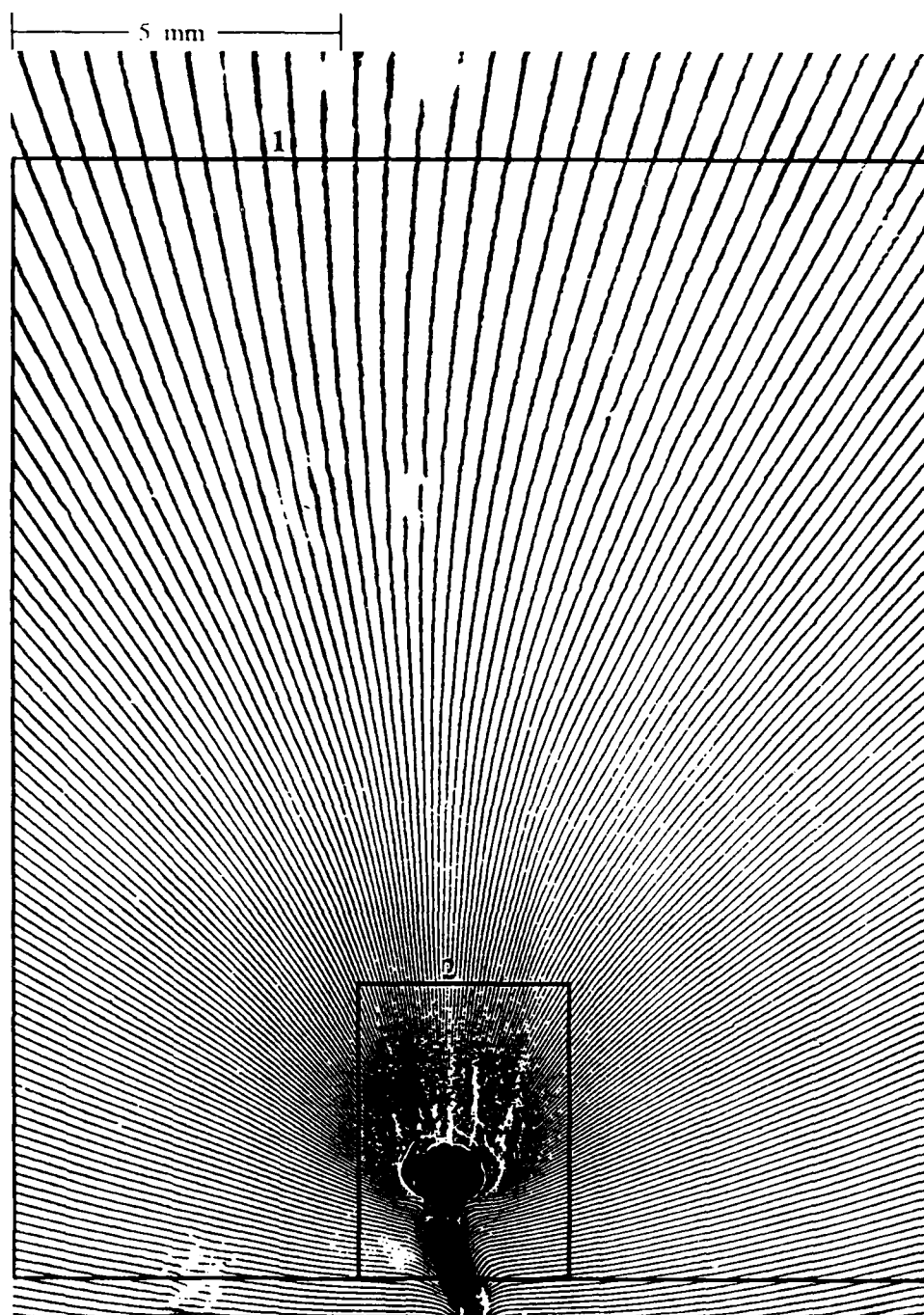
Figure 4a. v-Displacement in 5052-H32 Aluminum Specimens, MD031188(1), $\Delta a = 0.75$ (mm), $F_y = 5760$ (N).
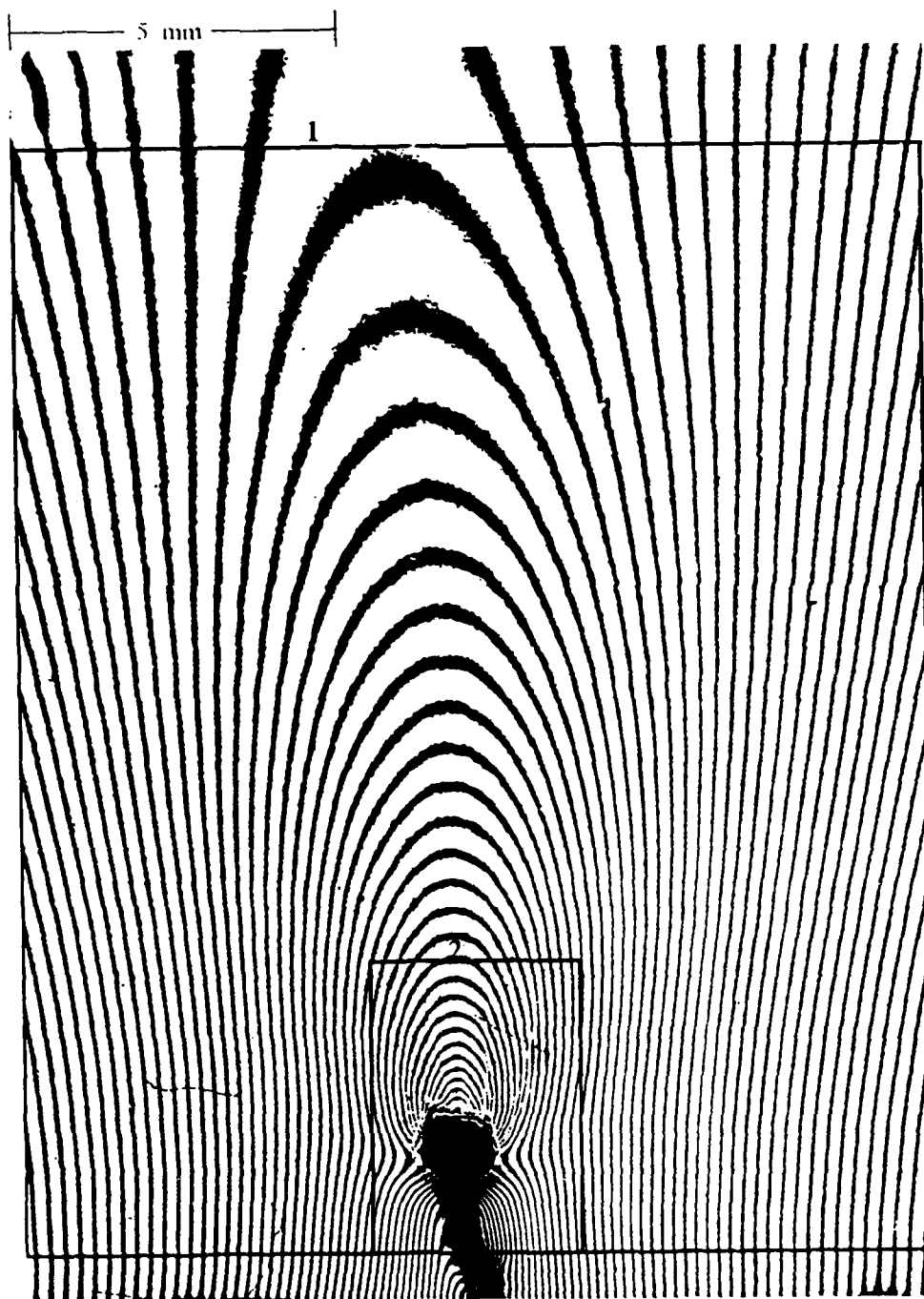
Figure 4b. u-Displacement in 5052-H32 Aluminum Specimen, MD031188(1), Δa = 0.75 (mm), F_y = 5760 (N).
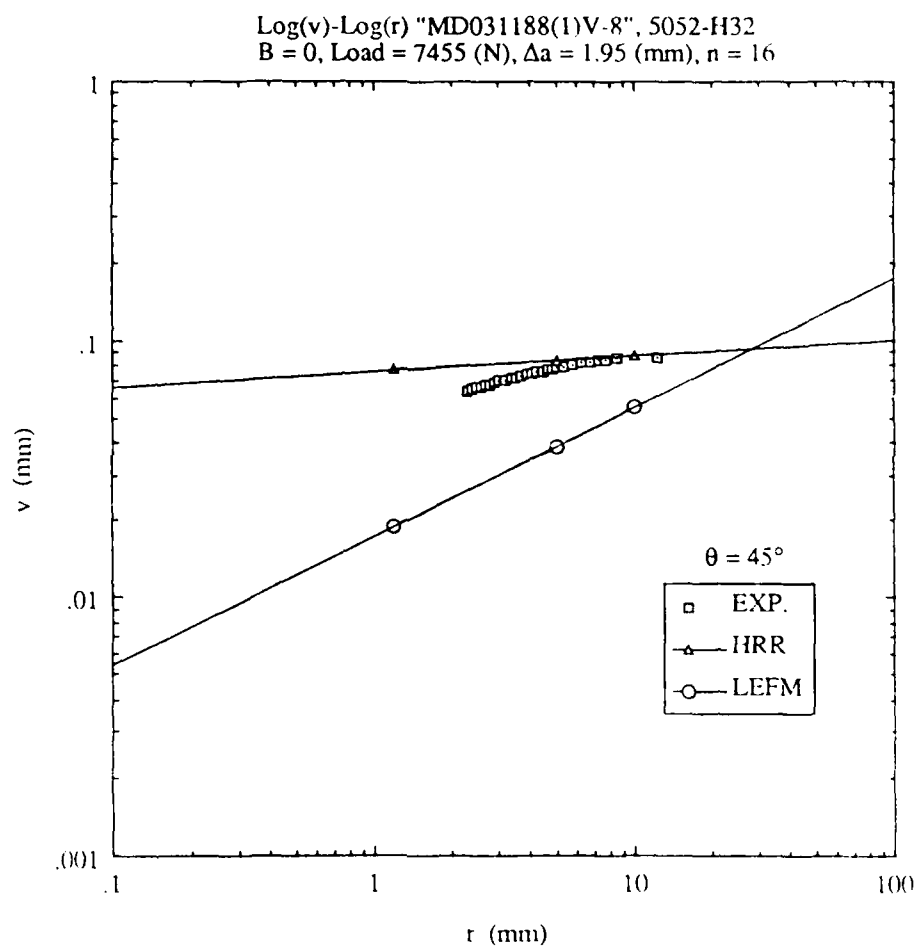
Figure 5. v-Displacement versus r Relation of the Experiment, LEFM and HRR at $\theta = 45°$, 5052-H32 Aluminum Specimen, MD031188(1)-8.
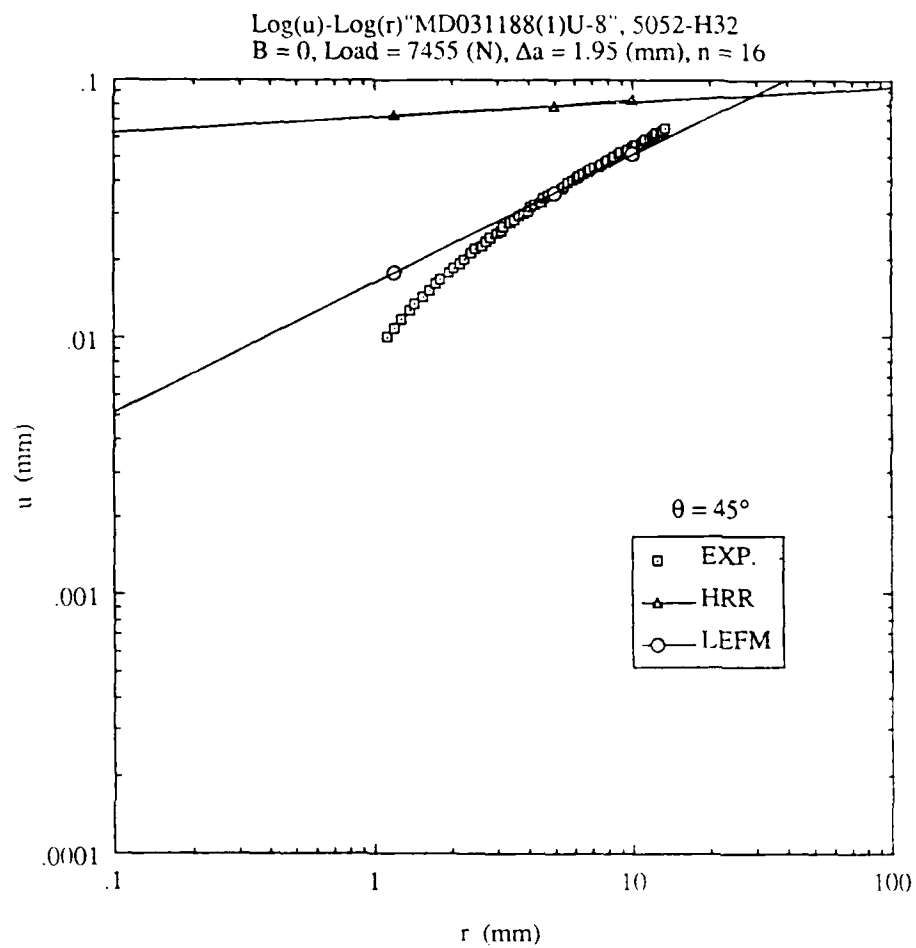
Figure 6. u-Displacement versus r Relation of the Experiment, LEFM and HRR at θ = 45°, 5052-H32 Aluminum Specimen, MD031188(1)-8.

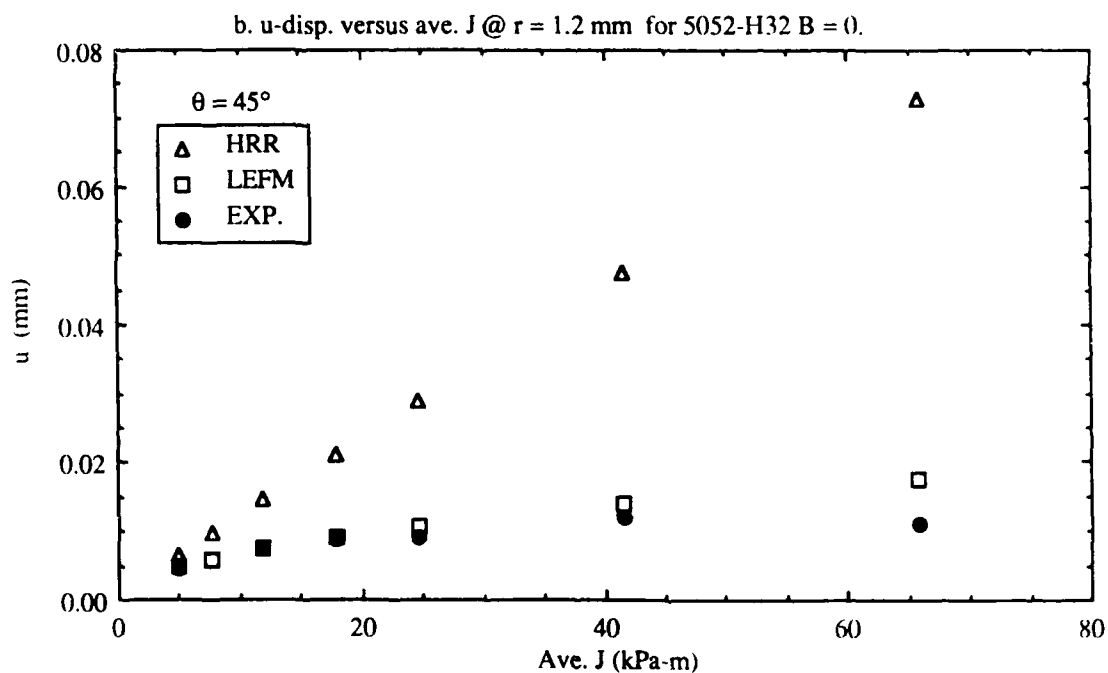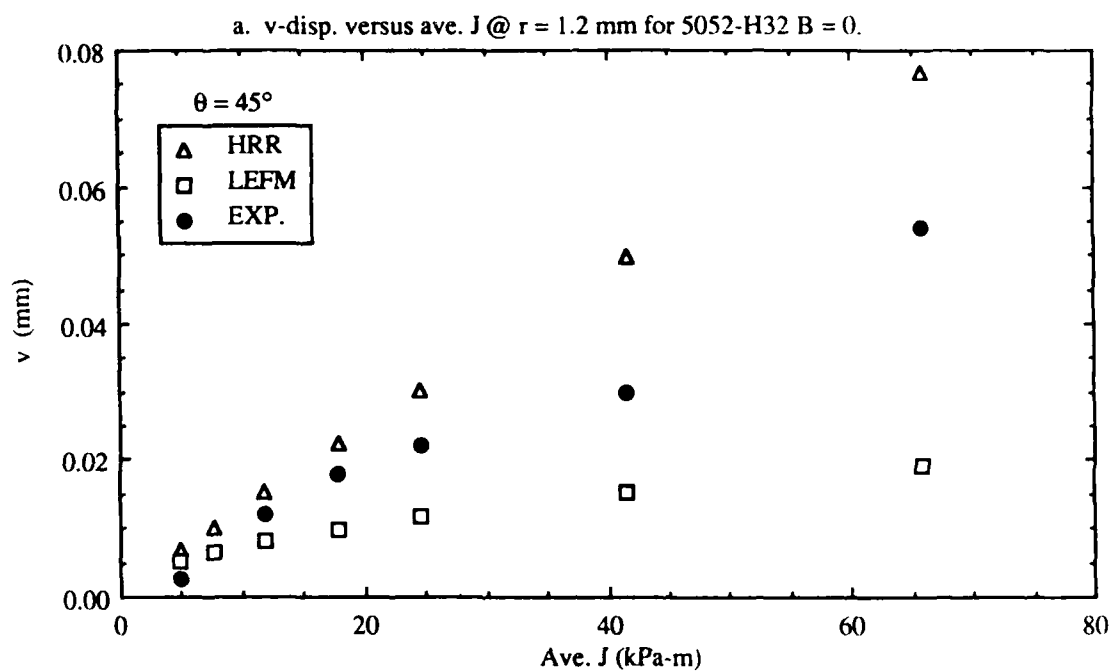a. v-disp. versus ave. J @ r = 1.2 mm for 5052-H32 B = 0.

b. u-disp. versus ave. J @ r = 1.2 mm for 5052-H32 B = 0.

Figure 7.   v- and u-Displacements   (r = 1.2 mm and θ = 45°) Versus Average J.   5052-H32 Aluminum MD031188(1)

a. v-disp. versus ave. J @ r = 5 mm for 5052-H32 B = 0.

b. u-disp. versus ave. J @ r = 5 mm for 5052-H32 B = 0.
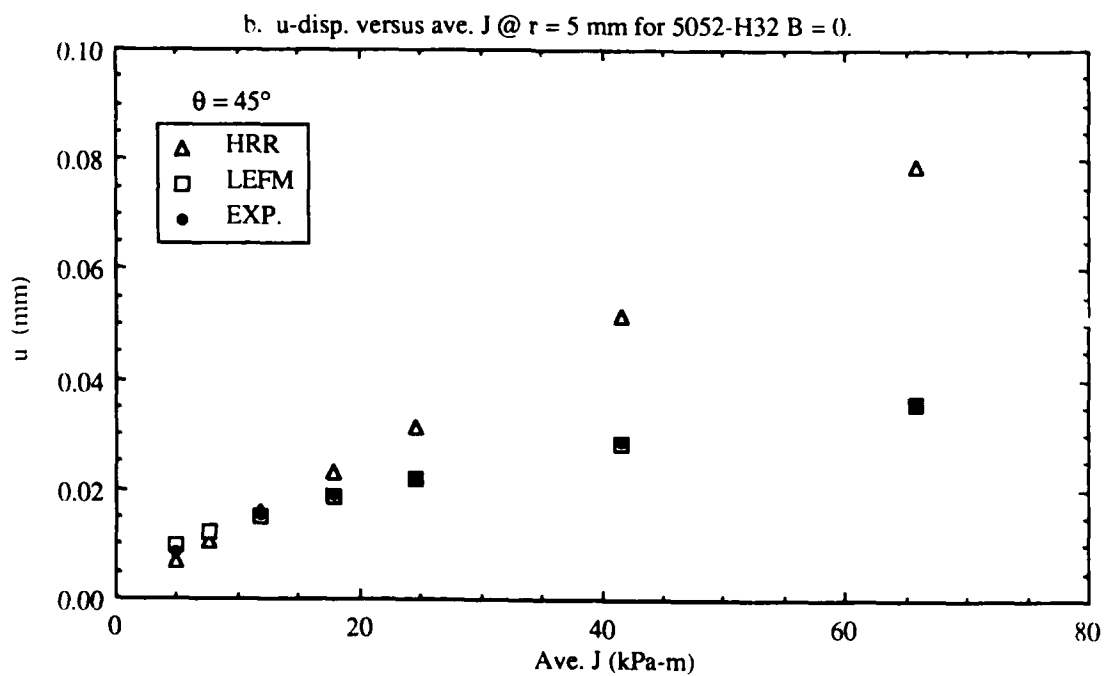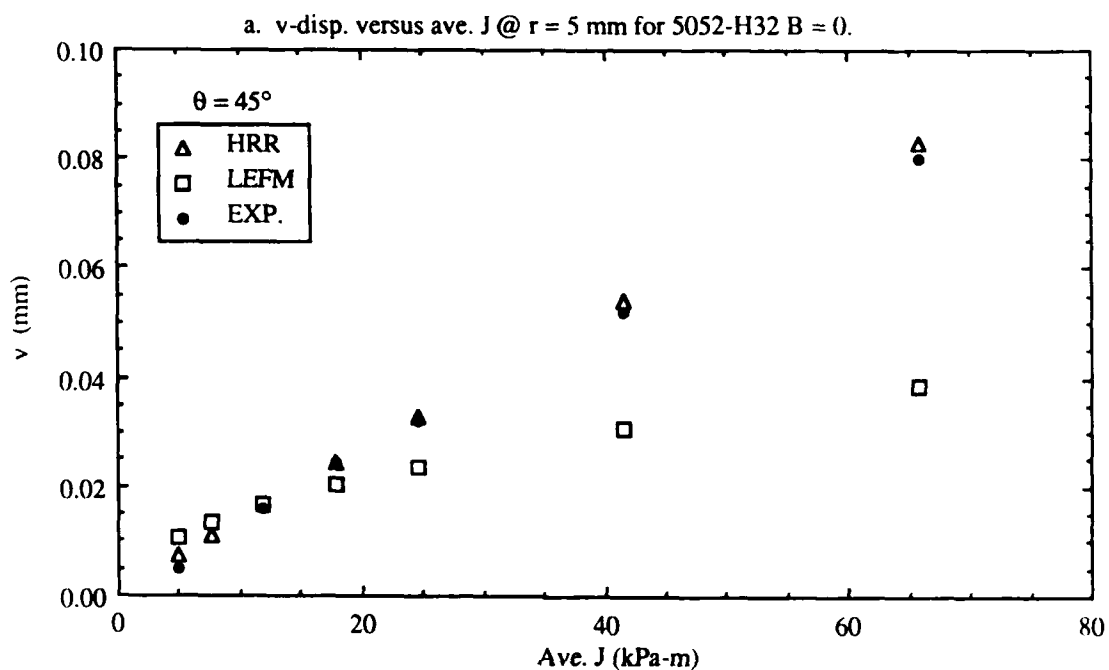
Figure 8.   v- and u-Displacements   (r = 5 mm and θ = 45°) Versus Average J.   5052-H32 Aluminum MD008188(1).

J-Resistance MD031188(1) 5052-H32" B = 0.

□ Contour 1
○ Contour 2
△ Contour 3
◇ Kang-Kobayashi 1987

Δa (mm)

J (Pa-m)
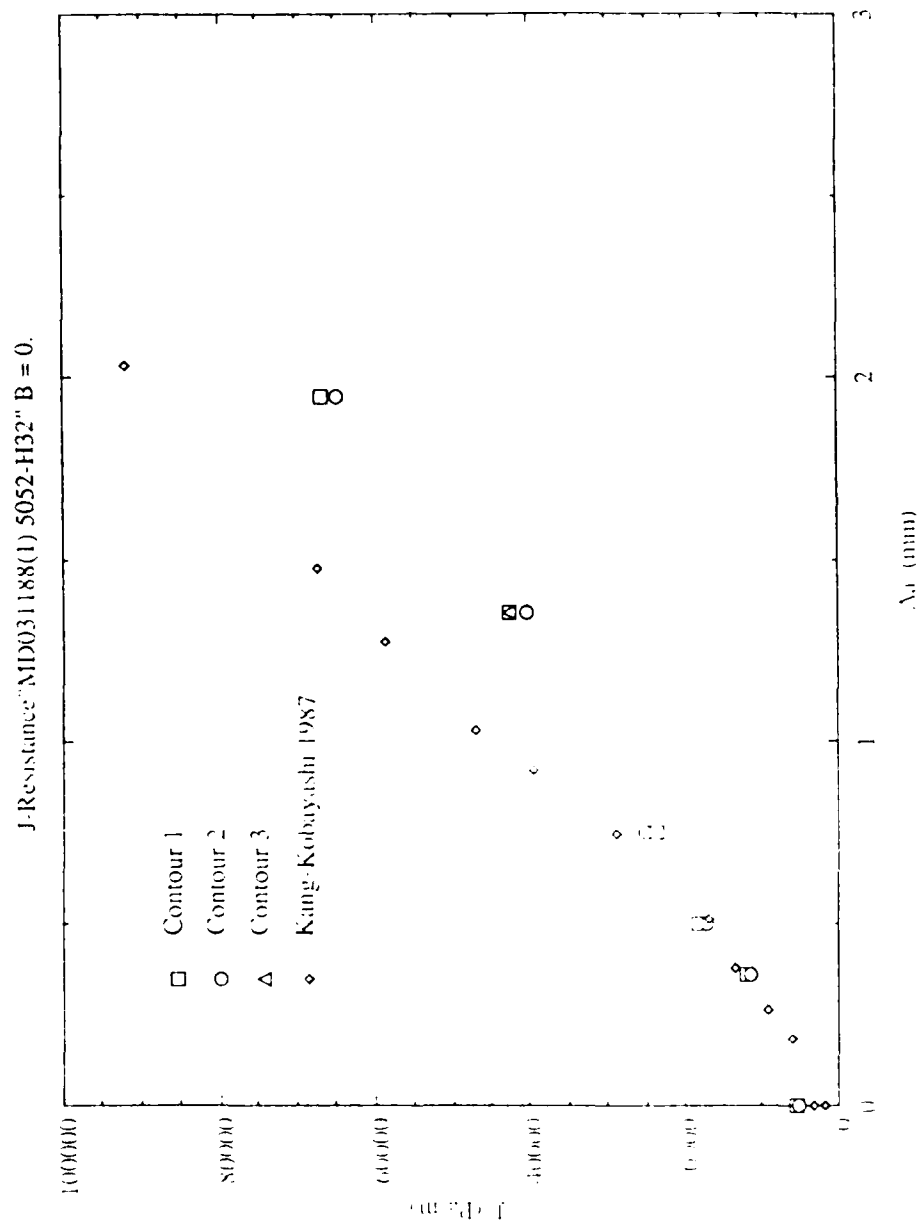
Figure 9.   J-Resistance Curves for 5052-H32
Cruciform Aluminum Specimen, MD031188(1)
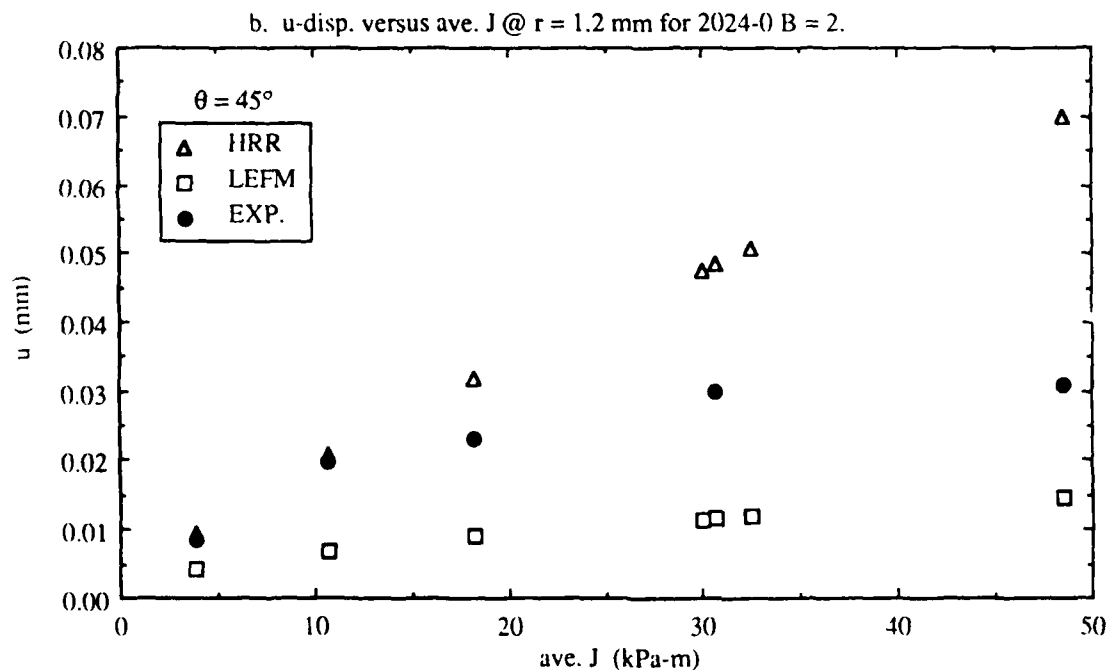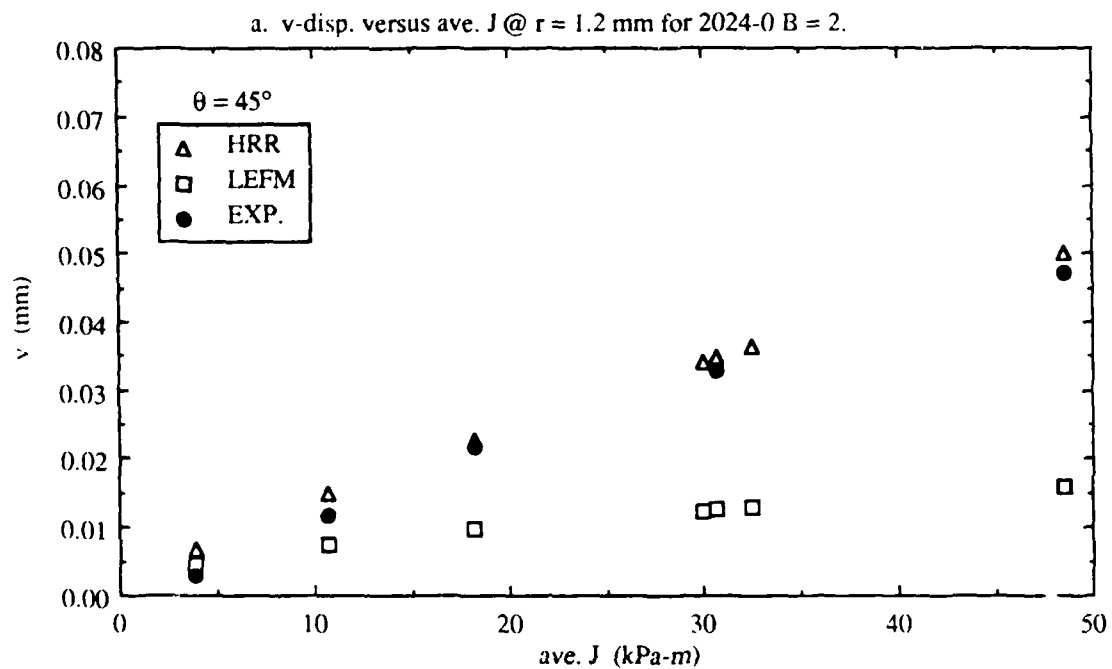
Figure 10. v- and u-Displacements (r = 1.2 mm and θ = 45°) Versus Average J. 2024-0 Aluminum MD050388.

a. v-disp. versus ave. J @ r = 1.2 mm for 2024-T3 B = 0.

θ = 45°

- △ HRR
- □ LEFM
- ● EXP.

v (mm) vs Average J (kPa-m)

b. u-disp. versus ave. J @ r = 1.2 mm for 2024-T3 B = 0.

θ = 45°

- △ HRR
- □ LEFM
- ● EXP.

u (mm) vs Average J (kPa-m)
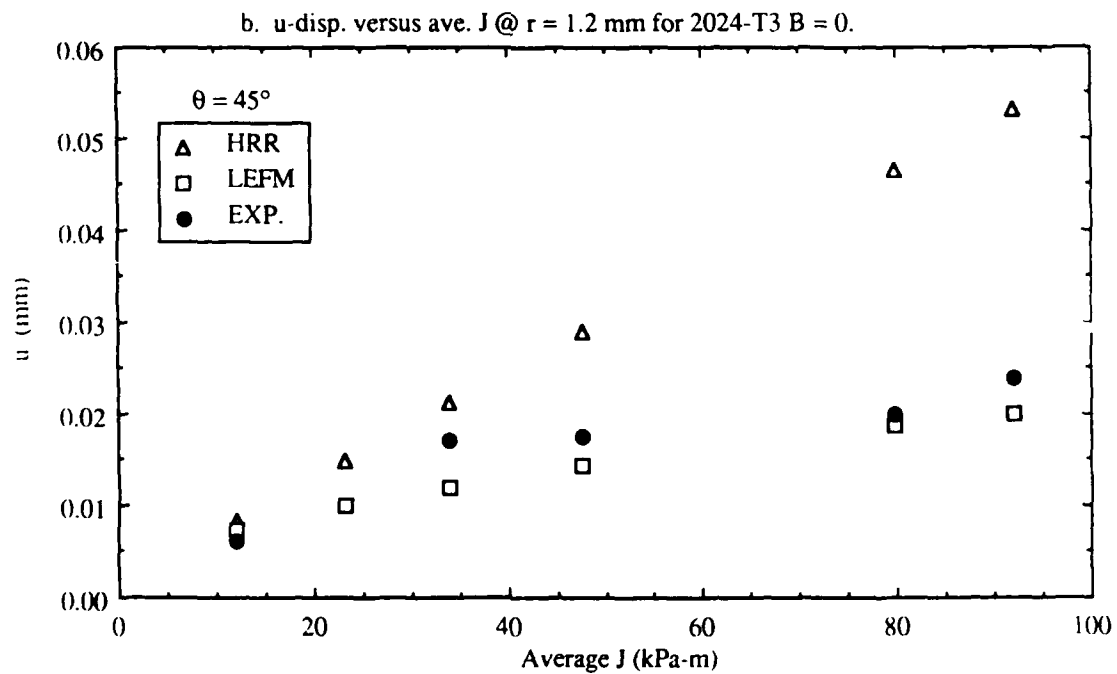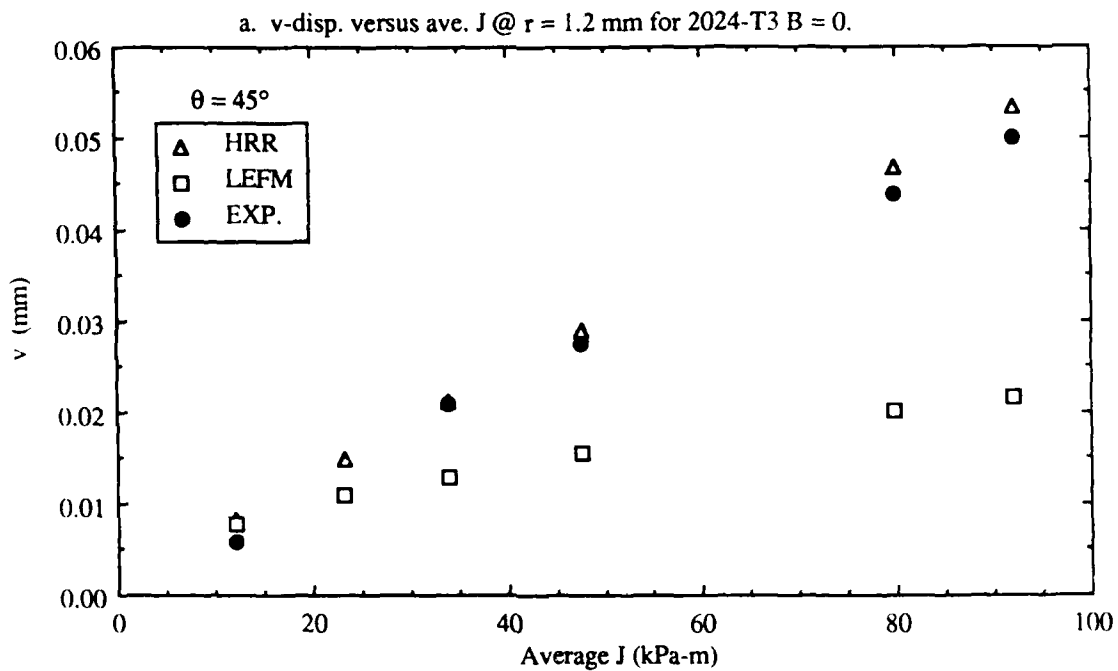
Figure 11. v- and u-Displacements (r = 1.2 mm and θ = 45°) Versus Average J. 2024-T3 Aluminum MD031687

Office of Naval Research
800 N Quincy Street
Arlington, VA 22217-5000
Attn: Code 11325M (4 copies)

Office of Naval Research
800 N Quincy Street
Arlington, VA 22217-5000
Attn: Code 1131

Defense Documentation Cntr
(4 copies)
Cameron Station
Alexandria, VA 02314

Naval Research Laboratory
Washington, DC 20375
Attn: Code 6000

Naval Research Laboratory
Washington, DC 20375
Attn: Code 6300

Naval Research Laboratory
Washington, DC 20375
Attn: Code 6380

Naval Research Laboratory
Washington, DC 20375
Attn: Code 5830

Naval Research Laboratory
Washington, DC 20375
Attn: Code 6390

Naval Research Laboratory
Washington, DC 20375
Attn: Code 2620

David W. Taylor Naval Ship
R & D Center
Annapolis, MD 21402
Attn: Code 28

David W. Taylor Naval Ship
R & D Center
Annapolis, MD 21402
Attn: Code 2812

David W. Taylor Naval Ship
R & D Center
Annapolis, MD 21402
Attn: Code 2814

David W. Taylor Naval Ship
R & D Center
Annapolis, MD 21402
Attn: Code 1700

David W. Taylor Naval Ship
R & D Center

Annapolis, MD 21402
Attn: Code 1720

David W. Taylor Naval Ship
R & D Center
Annapolis, MD 21402
Attn: Code 1720.4

Naval Air Development
Center
Warminster, PA 18974
Attn: Code 6043

Naval Air Development
Center
Warminster, PA 18974
Attn: Code 6063

Naval Surface Weapons
Center
White Oak, MD 20910
Attn: Code R30
       Technical Library

Naval Surface Weapons
Center
Dahlgren, VA 22448
Attn: Technical Library

Naval Civil Eng Library
Port Hueneme, CA 93043
Attn: Technical Library

Naval Underwater Systems
Center
New London, CT 06320
Attn: Code 44
       Technical Library

Naval Underwater Systems
Center
Newport, RI 02841
Attn: Technical Library

Naval Weapons Center
China Lake, CA 99555
Attn: Technical Library

NRL/Underwater Sound
Reference Dept.
Orlando, FL 32856
Attn: Technical Library

Chief of Naval Operations
Department of the Navy
Washington, DC 20350
Attn: Code OP-098

Commander
Naval Sea Systems Command
Washington, DC 20362

Attn: Code 05R25

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 05R26

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 09B31

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 55Y

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 55Y2

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 03D

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 7226

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 310A

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 310B

US Naval Academy
Mechanical Engineering Dept.
Annapolis, MD 21402

Naval Postgraduate School
Monterey, CA 93940
Attn: Technical Library

Mr. Jerome Persh
Stf Speclt for Matls &Struct
OUSDE & E. The Pentagon
Room 301089
Washington, DC 20301

Professor J. Hutchinson
Harvard University
Div. of Applied Sciences
Cambridge, MA 02138

Dr. Harold Liebowitz, Dean
School of Engr. & Applied Sci.
George Washington
University

Washington, DC 20052

Professor G.T. Hahn
Vanderbilt University
Dept. of Mech. & Matrls. Engr.
Nashville, TN 37235

Professor Albert S. Kobayashi
Dept. of Mechanical
Engineering
University of Washington
Seattle, WA 98195

Professor L.B. Freund
Brown University
Division of Engineering
Providence, RI 02912

Professor B. Budiansky
Harvard University
Division of Applied Sciences
Cambridge, MA 02138

Professor S.N. Atluri
Georgia Institute of
Technology
School of Engr. & Mechanics
Atlanta, GA 30332

Professor G.Springer
Stanford University
Dept. of Aeronautics
 & Astronautics
Stanford, CA 94305

Professor H.T. Hahn
Washington University
Center for Composites
Research
St. Louis, MO 63130

Professor S.K. Datta
University of Colorado
Dept. of Mechanical
Engineering
Boulder, CO 80309

Dr. M.L. Williams
School of Engineering
University of Pittsburgh
Pittsburgh, PA 15261

Dr. D.C. Drucker
Dept. of Aerospace Eng. &
Mechanics
University of Florida
Tallahassee, FL 32611

Dean B.A. Boley
Dept. of Civil Engineering
Northwestern University
Evanston, IL 60201

Professor J. Duffy
Brown University
Division of Engineering
Providence, RI 02912

Professor J.D. Achenbach
Northwestern University
Dept of Civil Engineering
Evanston, IL 60208

Professor F.A. McClintock
Dept of Mechanical
Engineering
Massachusetts Institute of
Technology
Cambridge, MA 02139

Professor D.M. Parks
Dept of Mechanical
Engineering
Massachusetts Institute of
Technology
Cambridge, MA 02139

Dr. M.F. Kanninen
Southwest Research Institute
PO Drawer 28510
6220 Culebra Road
San Antonio, TX 78284

Professor F.P. Chiang
Dept of Mechanical Engr
State U of NY at Stony Brook
Stony Brook, NY 11794

Professor S.S. Wang
Dept of Theoretical & Appl
Mechs
University of Illinois
Urbana, IL 61801

Professor Y. Weitsman
Civil Engr Department
Texas A&M University
College Station, TX 77843

Professor I.M. Daniel
Dept of Mechanical Engr
Illinois Institute of
Technology
Chicago, IL 60616

Professor C.T. Sun
School of Aeronautics &
Astronautics
Purdue University
W. Lafayette, IN 47907

Professor J. Awerbuch
Dept of Mech Engr &
Mechanics
Drexel University
Philadelphia, PA 19104

Professor T.H. Lin
University of California
Civil Engineering Dept
Los Angeles, CA 90024

Professor G.J. Dvorak
Dept of Civil Engr
Rensselaer Polytecnic
Institute

Troy, NY 12180

Dr. R.M. Christensen
Chemistry & Mtrl Sci Dept
Lawrence Livermore Natl Lab
PO Box 80P
Livermore, CA 94550

Professor J.R. Rice
Division of Applied Sciences
Harvard University
Cambridge, MA 02138

Professor W.N. Sharpe
The Johns Hopkins University
Dept of Mechanics
Baltimore, MD 21218

Professor C.F. Shih
Brown University
Division of Engineering
Providence, RI 02912

Professor A. Rosakis
California Institute of Tech
Graduate Aeronautical Labs
Pasadena, CA 91125

Professor D. Post
VA Polytechnic & State U
Dept of Engr Science &
Mechanics
Blacksburg, VA 24061

Professor W. Sachse
Cornell University
Dept of Theoretical &
 Applied Mechanics
Ithaca, NY 14853

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER UWA/DME/TR-88/61	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* FURTHER STUDIES OF THE HRR FIELD OF A MOVING CRACK, AN EXPERIMENTAL ANALYSIS		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER UWA/DME/TR-88/61
7. AUTHOR(*s*) M.S. DADKHAH, A.S. KOBAYASHI		8. CONTRACT OR GRANT NUMBER(*s*) N00014-85-K-0187
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Mechanical Engineering, FU-10 University of Washington, Seattle, WA 98195		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of the Chief of Naval Research Arlington, VA 22217-5000		12. REPORT DATE December 1988
		13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS*(If different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Unlimited

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

HRR Field, J-integral, Biaxial Loading, LEFM, Moire Interferometry, Elastic-Plastic Fracture Mechanics, Simultaneous Displacement Field, J-Dominance, J-resistance, Curve and Stable Crack Growth.

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*
An improved moire interferometry was used to record simultaneously both the vertical and horizontal displacements associated with stable crack growth in an uniaxially loaded 5052-H32 aluminum, single edge notched specimens. For stable crack growth up to 2 mm, the vertical displacement field showed the dominance of the HRR field. HRR field was detected in the horizontal displacement only at the initial stage of loading. The far and near field J-integrals were path independent during this incremental crack extension. These results and previous results involving 2024-0 and 2-24-T3 aluminum specimens indicate that (over)

DD ₁ FORM JAN 73 1473   EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

20. Abstract (cont.)

J-characterization of a crack, is not valid for such ductile materials in this specimen configuration.